Coherent Probing and Saturation of a Strongly Coupled Quantum Dot

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Abstract: We coherently probe a quantum dot, strongly coupled to a photonic crystal nano-cavity, using a resonant laser beam. At higher pump power, the coupled system's response becomes highly nonlinear. This coherent probing method has applications for classical and quantum information processing.

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Cavity quantum electrodynamics in solid state systems offers a scalable and robust platform for quantum optics research and the development of quantum information processing applications. In this approach, researchers aim to create a quantum network, which combines the utility of the photon as an information carrier with the nonlinearity of an atomic system for interacting more than one quantum bit (qubit) in a gate. The quantum network requires a way to coherently probe an atom or quantum dot in a cavity.

In this research, we present a novel method to probe a single InAs quantum dot (QD) that is strongly coupled to a photonic crystal (PC) cavity, using a laser beam resonant with the quantum dot. We show that the quantum dot strongly modifies the cavity transmission and reflection spectra [2]. Cavity-resonant photons are prohibited from passing through the cavity at the QD resonance. At high probe intensity, the quantum-dot induced reflectivity feature vanishes as the quantum dot becomes saturated. This giant optical nonlinearity occurs at a level of one photon per quantum dot lifetime.

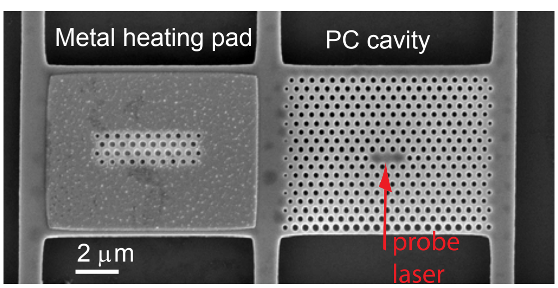

Fig. 1. Photonic crystal structure.

The structure consists of a linear three-hole defect cavity in a triangular photonic crystal lattice, as shown in Fig.1. It is fabricated in GaAs and contains a central layer of InAs quantum dots. The cavity has quality factor $Q = 10^4$, as shown in the photoluminescence spectra in Fig.2(a). In this figure, the sample is maintained near 25°K while local temperature of the sample is scanned between spectra. The QD and cavity tune at different rates, so that we can observe the anti-crossing behavior characteristic of a strongly coupled emitter and cavity.

This system is then probed by reflecting a narrow-bandwidth laser beam that is near resonance with the QD and cavity. By changing the probe wavelength, we probe the QD at different detunings with respect to the cavity at low probe power. The reflectivity measurements are shown in Fig. 2(b). Instead a Lorentzian-shaped cavity spectrum, a drop in the reflected signal is observed at the QD wavelength, as expected from theory[1] (fits).

When the probe power is increased, we can explore the nonlinear behavior of the QD/cavity system. Fig.2(c) shows the QD-induced reflectivity dip vanishing as P_{in} is increased. The saturation sets in as there is approximately one photon coupled to the cavity per modified quantum dot lifetime, which corresponds to an average cavity photon population near one. We observe agreement with theory by a steady-state solution

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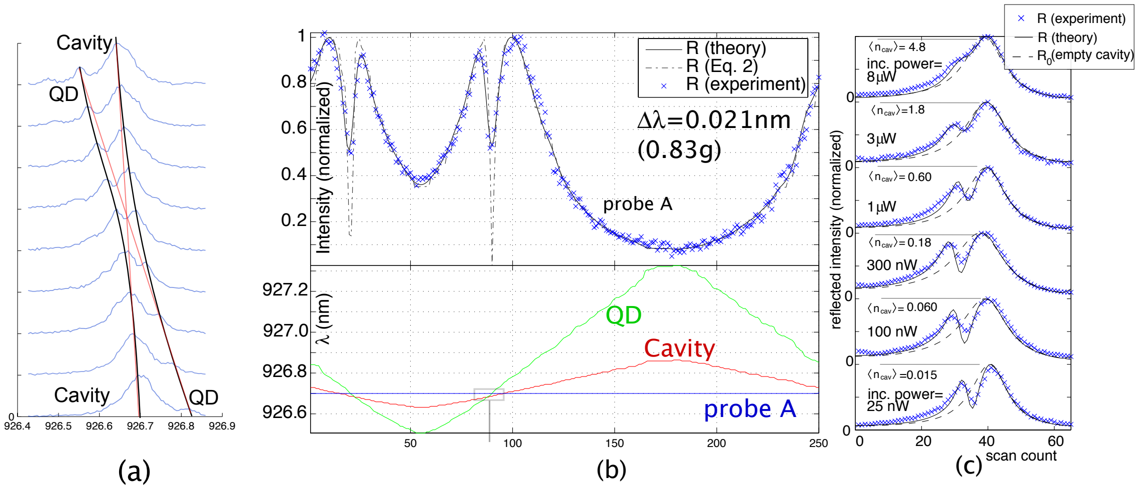

Fig. 2. (a) Photoluminescence measurements of a quantum dot strongly coupled to the photonic crystal nanocavity. As local temperature is scanned, the QD and cavity tune at different rates and show anticrossing. (b) Reflectivity of the probe beam off the same system. The bottom panel shows the tuning behavior of the quantum dot and cavity. (c) The QD-induced reflectivity dip is saturated at an average intensity of ~ 1 photon in the cavity.

of the quantum master equation (solid lines). We also verified that the QD-induced reflectivity dip vanishes controllably when excitons are (incoherently) generated by excitation with an above-GaAs-bandgap laser beam.

The measurements presented here provide both a novel method for probing the cavity-quantum dot system and the first steps toward the realization of quantum devices based on coherent light scattering from quantum dots in photonic crystal cavities. The giant optical nonlinearity is promising as a way to interact two or more photons, enabling photon number detection and two-qubit gates. It may also find applications in classical all-optical signal processing.

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